

Survival of superconducting correlations across the 2D superconductor-insulator transition: A finite frequency study

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The complex AC conductivity of thin highly disordered InO_x films was studied as a function of magnetic field through the nominal 2D superconductor-insulator transition. We have resolved a significant finite frequency superfluid stiffness well into the insulating regime, giving the first direct evidence for superconducting correlations in the insulating state of an amorphous film. A phase diagram is established that includes the superconducting state, a transition to a ‘Bose’ insulator and an eventual crossover to a ‘Fermi’ insulating state at high fields. We speculate on the consequences of these observations and their impact on the understanding of the insulating state and purported intervening low temperature metal.

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A quantum phase transition (QPT) is a zero temperature change of state as a function of some non-thermal parameter (pressure, doping, magnetic field, etc.)^{1,2}. The 2D superconductor-insulator quantum phase transition is a particularly beautiful and illustrative one, reflecting a transition between the two eigenstates at the extremes of a superconductor’s fundamental uncertainty relation between phase and particle number ($\Delta\theta\Delta n > 1$). One of the key questions here is the nature of the zero temperature destruction of the superconducting state. Does it proceed in a mean-field fashion by destruction of the amplitude Δ of the superconducting order parameter $\psi = \Delta e^{i\theta}$ or is it dominated by fluctuations of the superconducting phase θ ? The manner in which the superconductivity is destroyed is an issue that has direct relevance to many other important problems including that of high-temperature superconductivity³.

A related matter is the nature of the insulating state. There have been a number of proposals for an insulator with strong superconducting correlations. For instance, Fisher and co-workers^{4,5} postulated a dual description - the so-called ‘dirty boson’ model - of the SIT in which the superconducting state reflects the condensation of Cooper pairs and localization of vortices, while the insulating state is characterized by condensed vortices and localized Cooper pairs. More recently, it has been proposed that the transition is an inhomogeneous one⁶, and where global superconductivity may obtain by percolation of locally superconducting clusters⁷. To date, evidence for superconducting signatures in the insulating state may have been found in signs of vortex activation in insulating films⁸ as well as in a crossover of the Hall coefficient R_{xy} ⁹ at a field higher than the superconductor-insulator critical field H_{SIT} . Although these results have been suggestive there has been a notable lack of direct evidence for superconducting correlations in the insulator. Moreover a number of outlying issues remain. For

instance, the Cooper pair gap appears to close on the approach to the SIT in amorphous films, evidence seemingly incompatible with the existence of localized Cooper pairs^{10,11}. Still others have challenged the existence of a direct transition between superconducting and insulating states altogether and instead postulate the existence of an intervening metal¹².

In this Letter we present the results of a comprehensive study of the complex AC conductivity through the nominal 2D SIT in InO_x thin films using microwave cavities. Here, we have resolved a significant finite frequency superfluid stiffness in the insulating state which persists up to resistances over $10^6 \text{ Ohms}/\square$ and fields up to $3\times$ the critical field, giving the first direct evidence for a state with localized Cooper pairs. This establishes a phase diagram with distinct regions dominated by superconducting, ‘Bose’ insulating, and ‘Fermi’ insulating effects.

Samples were 200 Å-thick 3mm-diameter highly-disordered amorphous indium oxide ($\alpha\text{-InO}$) thin films prepared by e-gun evaporating high purity (99.999%) In_2O_3 on clean 19mm-diameter sapphire discs in high vacuum^{13,14}. Post-deposition, samples were room-temperature annealed for approximately one week in ambient air and then, except for short periods, were kept well below LN_2 temperatures for the duration of the measurements (approximately 2 months). TEM measurements show diffuse rings with no diffraction spots, suggesting the amorphousness of the films with no crystalline inclusions. AFM images show continuous films with no voids or cracks and are completely featureless down to a scale of a few nm (the resolution of the AFM). Experiments were performed in a novel cryomagnetic resonant microwave cavity system. The cavity diameter was chosen to optimize performance in the 22 GHz ($\hbar\omega/k_B = 1.06 \text{ K}$) TE011 mode, but measurements were possible at a number of discrete frequencies from 9 to 110 GHz. Cavities were operated at a power low enough

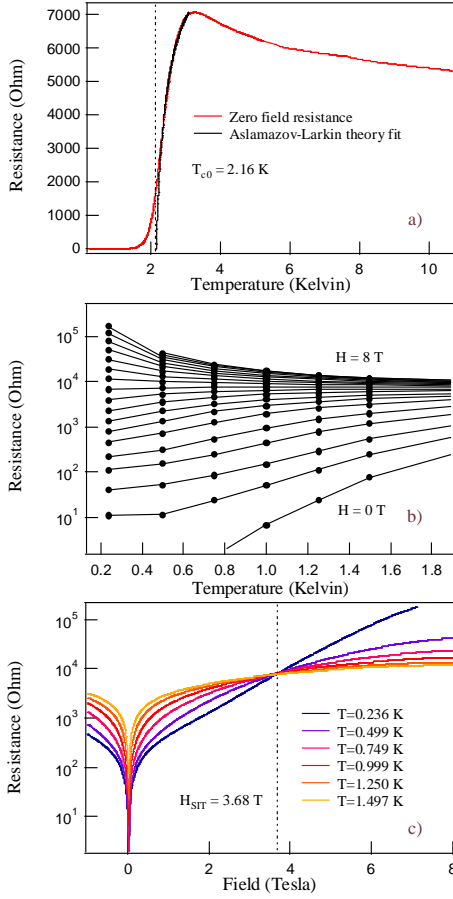


FIG. 1: (a) DC zero field sheet resistance vs. temperature, together with a fit to the AL form with mean-field transition temperature $T_{c0} = 2.16$ K. (b) DC Sheet resistance vs. temperature for field values $H=0, 0.05, 0.1, 0.25, 0.5, 1, 1.5, 2.5, 3, 3.5, 4, 4.5, 5, 5.5, 6, 6.5, 7, 7.5, 8$ Tesla. (c) Sheet resistance vs. magnetic field for temperatures shown. The crossing point determines a critical field of 3.68 Tesla.

to prevent sample heating. Various well-known relations were used to relate the resonances' frequency shift $\Delta\omega$ and change in quality factor ΔQ upon sample introduction to the complex conductivity^{15,16,17,18}. The conversions from ΔQ and $\Delta\omega$ to conductivity were made by normalizing the AC resistance of the cavity data to DC data at temperatures well above the occurrence of superconductivity and insisting that the superfluid stiffness (defined below), was frequency *independent* at zero field as $T \rightarrow 0$. DC resistance was measured on co-deposited samples in a two-probe configuration by low frequency AC lock-in techniques using excitation currents of $10\text{pA} - 10\text{nA}$. The probe's lead resistances, which have a negligible temperature dependence in the displayed temperature range, were well characterized and have been subtracted from the displayed data.

The zero field DC resistance curve shown in Fig. 1a is fairly typical for a highly disordered superconducting thin film showing an approximately log increase of R

with decreasing temperature, before the occurrence of a broad superconducting transition. As shown in Fig. 1b, when the field is increased the resistance curves cross over from a superconducting positive dR/dT to an insulating negative dR/dT behavior similar to previous field-tuned studies^{19,20,21}. When plotted as R vs H (Fig. 1c) the experimental data shows a low-temperature iso-resistance crossing point of 3.68 Tesla, which can be identified as the critical field of the SIT, H_{SIT} . The DC data can be shown to be consistent with previous studies^{19,20,21} that found scaling as a function of the reduced variable $|H - H_{SIT}|/T^{1/z\nu}$ where $z\nu$ is consistent with the exponent for 2D classical percolation $\frac{4}{3}$.

As the temperature is lowered, distinct regions typified by amplitude and then phase fluctuations of the superconducting order parameter $\psi = \Delta e^{i\theta}$ are expected. We can quantify the amplitude fluctuations at zero field by fitting the DC resistance curves to the Aslamazov-Larkin²² (AL) form for gaussian fluctuations. In two dimensions, the extracted temperature scale $T_{c0} = 2.16$ K does not signify the occurrence of a phase transition, but instead represents the temperature scale below which the Cooper pair amplitude becomes well defined and as such the AL form is not a good fit near T_{c0} itself.

We now turn our attention to the AC conductivity. At low temperatures, the imaginary conductivity for a long-range ordered superconductor is expected to have the form $\sigma_2 = \frac{Ne^2}{\omega m}$ where N is the superfluid density and e and m are the electronic charge and mass respectively. For a fluctuating superconductor one can define $\sigma_2 = \frac{N(\omega)e^2}{\omega m}$ where an additional frequency dependence is captured by a generalized frequency dependent superfluid density. The superfluid density is directly proportional to the superfluid stiffness which is the energy scale for inducing slips in the superconducting phase. In Fig. 2a we display the $H = 0$ generalized frequency dependent superfluid stiffness, T_θ (in degrees Kelvin) extracted via the relation $\sigma_2 = \sigma_Q \frac{k_B T_\theta}{\hbar \omega}$, where $\sigma_Q = \frac{4e^2}{\hbar d}$ is the quantum of conductance for Cooper pairs divided by the film thickness. The superfluid stiffness curves all cross the predictive line ($T_\theta = 4T_{KTB}$) for the Kosterlitz-Thouless-Berezinskii (KTB) transition in a range near 1.6 K. We associate this temperature as the KTB scale below which the superconductor becomes robust against vortex phase fluctuations. A somewhat similar phenomenology has been seen in quasi 2D high temperature superconductors at THz frequencies²³, although here the superfluid stiffness acquires a frequency dependence below the KTB scale. The T_{KTB} of 1.6 K and T_{c0} of 2.16 K give the temperatures at zero field for phase coherence and a well defined superconducting amplitude, respectively.

Displayed in Fig. 3 is the finite-frequency complex response at $H \neq 0$ for the 22 GHz data. Similar plots can be made at other frequencies. Fig. 3a shows the AC resistance measured over a range of temperatures and magnetic fields. We identify the region below the critical contour of $R = 2295\Omega$ (in bold) as the domain over which the underlying $T = 0$ superconducting phase has influ-

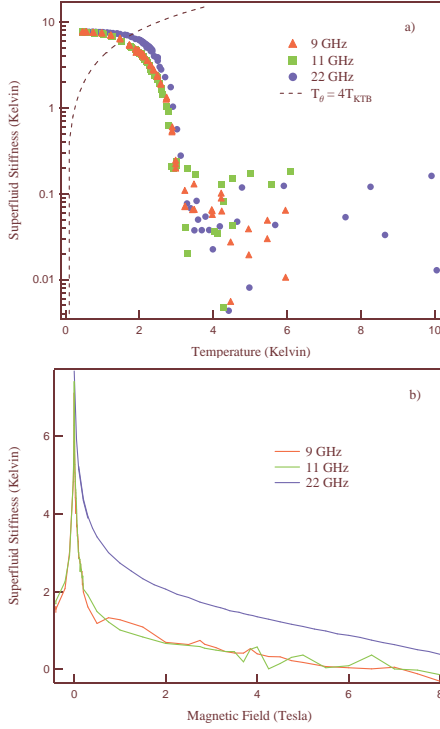


FIG. 2: Superfluid stiffness, T_{θ} ($\propto \omega \sigma_2$), extracted as described in the text. (a) Temperature dependence at $H=0$. Also shown is the theoretical T_{KTB} which intersects T_{θ} around $T = 1.6K$. (b) 0.5 K magnetic field dependence at select low frequencies.

ence. In Fig. 3b is shown the superfluid stiffness T_{θ} at 22 GHz, using the same conversion as above, and plotted as a function of temperature and magnetic field. The use of relatively high probing frequencies allows us to resolve superconducting fluctuations into the insulating part of the phase diagram. An additional advantage of our high frequencies is that they are at least two orders of magnitude higher than a generous estimate for the vortex depinning frequency²⁶ found in thin films of conventional superconductors. The vortex contribution to the optical response is therefore expected to be purely dissipative, leaving the superfluid as the only principal contributor to σ_2 ²⁴. The finite-frequency superfluid stiffness falls quickly with increasing field, but remains finite above H_{SIT} , well into the insulating regime to fields almost 3 times the critical field H_{SIT} . To the best of our knowledge this is the first direct measure of superconducting correlations on the insulating side of the 2D superconductor-insulator transition in an amorphous film.

Our observation of a finite frequency superfluid stiffness at $H > H_{SIT}$ is not inconsistent with an insulating $T=0$ groundstate. As alluded to above, our experiments are sensitive to superfluid *fluctuations* because we probe the system on short time scales via an experimental frequency ω_{Exp} that is presumably high compared to an intrinsic order parameter fluctuation rate ω_{QC} close to the

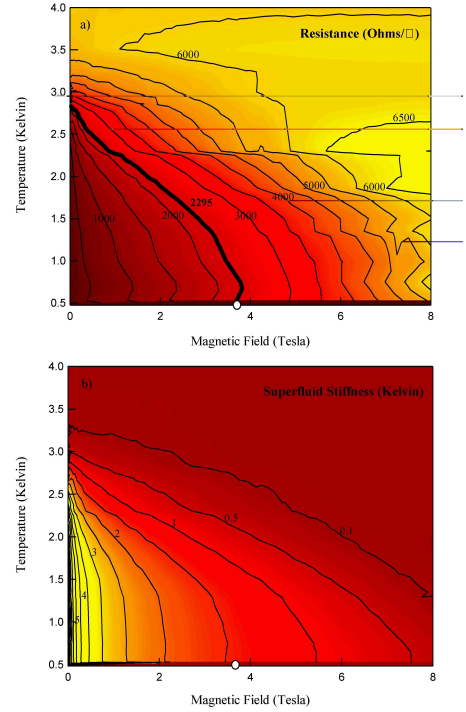


FIG. 3: (a) AC Sheet resistance ($\propto Re(\frac{1}{\sigma_d})$) and (b) Superfluid stiffness ($\propto \omega \sigma_2$) at 22 GHz. The critical field, H_{SIT} , is shown as a white dot at $H = 3.68T$. Yellow indicates maximum.

transition. Above H_{SIT} , an experimental probe in the limit $\omega_{Exp} \ll \omega_{QC}$ will not detect superfluid fluctuations as a system with $T_{\theta}(\omega \rightarrow 0) \neq 0$ can support superfluid flow, behavior obviously incompatible with the notion of an insulator. On general grounds an insulator with $\sigma_1 = 0$ at zero frequency, must have a σ_2 that is negative at $\omega = 0^+$ by Kramers-Kronig considerations, meaning that such a system can not appear superconducting at low frequencies. It is only by using a relatively high ω probe we detect these fluctuations. Returning to Fig. 2b we see the dramatic drop in superfluid stiffness with increasing field and the strong frequency dependence of T_{θ} which reflects that the Cooper pairs are correlated on time scales that can be resolved at the probing frequency, so that while long range order does not exist at finite T , short-range correlations do. We also note that at low temperatures and well into the insulating side of the phase diagram, that although the magnitude of the superfluid stiffness is of the same order as it above T_{c0} , the signal becomes temperature independent at low temperature showing the intrinsic quantum mechanical nature of these fluctuations.

We are able to extract a phase diagram that establishes the existence of superconducting correlations well into the insulating state. In Fig. 4 contours are plotted which denote the region above which our superfluid stiffness becomes almost indistinguishable from the normal state noise level (set at 1 % of the $T \rightarrow 0$, $H = 0$ super-

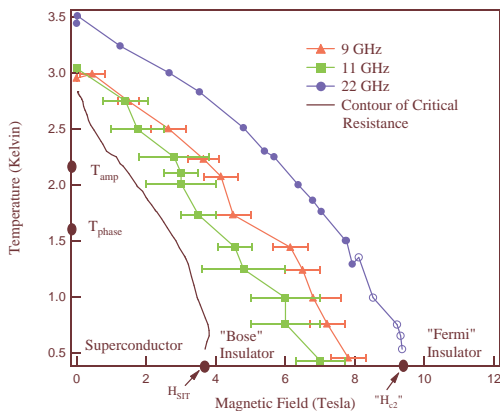


FIG. 4: 2D Field Tuned Superconductor-Insulator “Phase Diagram”. Contours with markers are the detection limit for T_θ at specified frequencies. Black dots on the temperature axis denote T_{amp} ($= T_{c0}$) and T_{phase} ($= T_{KTB}$), temperatures signifying the onset of amplitude and phase fluctuations, respectively. H_{SIT} appears as a black dot and the contour of critical resistance from Fig. 3a appears as a solid black line. Open symbols represent data obtained from a small linear extrapolation beyond our maximum field of 8 Tesla.

fluid stiffness), thereby giving a measure of the extent of superconducting correlations into the insulating regime. The noise is greatest for frequency contours away from our cavity’s optimal operating frequency of 22 GHz. It is evident that the higher frequency probe at 22 GHz allows one to examine the fluctuations of the order parameter persisting at fields higher than H_{SIT} and temperatures higher than T_{c0} , at shorter length and time scales than the 9 or 11 GHz probes. In the high-frequency limit one would expect that the detection limit would eventually extrapolate to a field where the Cooper pairs are completely depaired. For 22 GHz we observe that the data extrapolates to a value of $H=9.35$ T, which is close to the value of the pair breaking field, H_{c2} , found in similar films of InO_x ^{14,27,28} giving evidence that 22 GHz is near the high-frequency limit. It is impossible to say with our current results whether this pair breaking scale should be associated with orbital or spin effects. We do note that this field is well above the naive estimate ($H_P = 1.86 \times T_c$) of the Pauli pair breaking field, but that disorder is known to lead to enhanced H_{c2} over the expectation from its $H=0$ value²⁹. Our results and interpretation are not consistent with the inference of Ref.²⁷ that Cooper pairs still had integrity at fields many times the pair breaking scale.

It would interesting to verify whether the crossover observed in R_{xy} by Paalanen *et al.*⁹ - which has also been interpreted as a ‘Bose’ glass/‘Fermi’ glass crossover - is found in our films at the extrapolated pair breaking field scale.

We emphasize that we believe the only true phase transition in the system (neglecting for a moment the possibility of an intervening metal phase) is at H_{SIT} and that the contours in Fig. 4 give a frequency dependent crossover. We observe superconducting correlations not just asymptotically close to the SIT, but an extended region above H_{SIT} . This establishes for the first time a model-free, unambiguous picture of an insulating state that is dominated by superconducting correlations - a ‘Bose’ insulator. Our phase diagram is characterized by a superconducting groundstate, a phase transition to a ‘Bose’ insulating state at H_{SIT} and a crossover to ‘Fermi’ insulator near a depairing field “ H_{c2} ”.

This work raises certain questions about the expected electrodynamic response of the various proposed phases of matter. It might be expected, for instance, that the functional dependence of the DC $R(T)$ is different for ‘Fermi’ vs ‘Bose’ insulators, but these differences may be subtle and difficult to distinguish experimentally. In the present case, we have a heuristic argument about the detection of finite frequency superfluid stiffness as being indicative of the ‘Bose’ insulator, but detailed calculations are lacking. Moreover, it has been argued that an anomalous metallic state intervenes between the superconducting and insulating states at low temperature¹². At finite temperature the difference in the dissipative response between a fluctuating superconductor and this metal could be subtle, but the difference in the reactive response may be dramatic. Again, detailed calculations are lacking. In either case we have shown that the underlying superconductivity will manifestly have to be taken into account to describe the insulating and anomalous metallic states.

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